Axion Photon Oscillations From a "Particle-Antiparticle" View Point

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Abstract

We observe that it is very usefull to introduce a complex field for the axion photon system in an external magnetic field, when for example considered with the geometry of the experiments exploring axion photon mixing, where the real part is the axion and the imaginary part is the photon polarization that couples to the axion when the magnetic field is present. In the absence of the external magnetic field, the theory displays charge conjugation symmetry. In this formulation the axion and photon are the symmetric and antisymmetric combinations of particle and antiparticle (as defined from the complex field) respectively and they do not mix if the external magnetic field is set to zero. The magnetic field interaction is seen to be equivalent to first order to the interaction of the complex charged field with an external electric potential, where this ficticious "electric potential" is proportional to the external magnetic field. This interaction breaks the charge conjugation symmetry and therefore symmetric and antysymmetric combinations are not mantained in time. As a result one obtains axion photon mixing in the presence of an external magnetic field, a well known result understood in a different way.

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I. INTRODUCTION

The idea of the axion [1] has been the subject of many investigations. Although was originally introduced in order to solve the strong CP problem, it has been postulated as a candidate for the dark matter also. A great number of ideas and experiments for the search this particle have been proposed [2].

As for many pseudoscalar particles, for example among the already known particles like the neutral pion, the axion field ϕ has coupling to the electromagnetism through an interaction term of the form $g\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$.

A way to explore for observable consequences of the coupling of a light scalar to the photon in this way is to subject a beam of photons to a very strong magnetic field.

In this situation the axion photons system undergoes "oscillations".

This affects the optical properties of light which could lead to testable consequences[3]. Also, the produced axions could be responsible for the "light shining through a wall phenomena ", which are is obtained by first producing axions out of photons through the oscillations obtained in a strong magnetic field region, then subjecting the mixed beam of photons and axions to an absorbing wall for photons, but almost totally transparent to axions due to their weak interacting properties which can then go through behind this "wall", applying then another magnetic field one can recover once again some photons from the produced axions [4].

In this article we will show that axion photon system allows a very natural complex structure, and the theory aquires a very interesting form when one introduces a complex field that "unifies" the axion and the photon. It is possible in fact to introduce a complex field for the axion photon system in an external magnetic field, when for example considered with the geometry of the experiments exploring axion photon mixing, where the real part is the axion and the imaginary part is the photon polarization that couples to the axion when the magnetic field is present.

In the absence of the external magnetic field, the theory displays charge conjugation symmetry. In this formulation the axion and photon are the symmetric and antisymmetric combinations of particle and antiparticle (as defined from the complex field) respectively and they do not mix if the external magnetic field is set to zero. The magnetic field interaction is seen to be equivalent to first order to the interaction of the complex charged field with

an external electric potential, where this ficticious ”electric potential” is proportional to the external magnetic field. This interaction breaks the charge conjugation symmetry and therefore symmetric and antysymmetric combinations are not mantained in time. As a result one obtains axion photon mixing in the presence of an external magnetic field, a well known result understood in a different way.

II. ACTION AND EQUATIONS OF MOTION

The action principle describing the relevant light pseudoscalar coupling to the photon is

$$S = \int d^4x \Big[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 + \frac{g}{2} g \phi \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \Big] \tag{1}$$

We now specialize to the case where we consider an electromagnetic field with propagation only along the z-direction and where a strong magnetic field pointing in the x-direction is present. This field may have an arbitrary space dependence in z, but it is assumed to be time independent. In the case the magnetic field is constant, see for example [5] for general solutions.

For the small perturbations we consider only small quadratic terms in the action for the axion fields and the electromagnetic field, following the method of for example Ref. [5], but now considering a static magnetic field pointing in the x direction having arbitrary z dependence and specializing to z dependent electromagnetic field perturbations and axion fields. This means that the interaction between the background field , the axion and photon fields reduces to

$$S_I = \int d^4x \Big[\beta \phi E_x \Big] \tag{2}$$

where $\beta = gB(z)$. Choosing the temporal gauge for the photon excitations and considering only the x-polarization for the electromagnetic waves, since only this polarization couples to the axion, we get the following 1+1 effective dimensional action (A being the x-polarization of the photon)

$$S_2 = \int dz dt \Big[\frac{1}{2} \partial_\mu A \partial^\mu A + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 + \beta \phi \partial_t A \Big] \tag{3}$$

($A = A(t,z)$, $\phi = \phi(t,z)$), which leads to the equations

$$\partial_\mu \partial^\mu \phi + m^2 \phi = \beta \partial_t A \tag{4}$$

$$\partial_\mu \partial^\mu A = -\beta \partial_t \phi \tag{5}$$

As it is known, in temporal gauge, the action principle cannot reproduce the Gauss constraint (here with a charge density obtained from the axion photon coupling) and has to be impossed as a complementary condition. However this constraint is automatically satisfied here just because of the type of dynamical reduction employed and does not need to be considered anymore.

III. INTRODUCTION OF THE COMPLEX FIELD, CHARGE CONJUGATION SYMMETRY AND ITS BREAKDOWN

Without assuming any particular z-dependence for β, but still insisting that it will be static that the interaction term, after dropping a total time derivative can be expressed as

$$S_I = \frac{1}{2} \int dz dt \beta \Big[\phi \partial_t A - A \partial_t \phi \Big] \tag{6}$$

defining the complex field ψ as

$$\psi = \frac{1}{\sqrt{2}} (\phi + iA) \tag{7}$$

we see that in terms of this complex field, the axion photon density takes the form

$$S_I = \frac{1}{2} \int dz dt \beta i (\psi^* \partial_t \psi - \psi \partial_t \psi^*) \tag{8}$$

We observe that to first order in β, (8) that this interaction has the same form as that of scalar QED with an external "electric " field to first order. In fact the magnetic field or more precisely $\beta/2$ appears to play the role of an "analog external electric potential".

The free part of the action, that is the one containing kinetic and mass terms is in terms of the complex field ψ

$$S_{free} = \int dz dt \Big[\partial_\mu \psi^* \partial^\mu \psi - \frac{1}{4} m^2 (\psi^* + \psi)^2 \Big] \tag{9}$$

In the case the axion is taken to be massless an additional invariance, of phase change in the ψ field appears. This leads to a conserved current and the theory becomes very close to scalar QED, something that can be profitably exploited [6] . Now let us introduce the charge conjugation , that is,

$$\psi \rightarrow \psi^* \tag{10}$$

We see then that the free action (9) is indeed invariant under (10). The A and ϕ fields when acting on the on the free vacuum give rise to a photon and an axion respectivelly, but in terms of the particles and antiparticles defined in terms of ψ, we see that a photon is an antisymmetric combination of particle and antiparticle and an axion a symmetric combination, since

$$\phi = \frac{1}{\sqrt{2}}(\psi^* + \psi), A = \frac{1}{i\sqrt{2}}(\psi - \psi^*) \tag{11}$$

So that the axion is even under charge conjugation, while the photon is odd. These two eigenstates of charge conjugation will propagate without mixing as long as no external magnetic field is applied. The interaction with the extenal magnetic field is not invariant under (10), in fact under (10) we can see that

$$S_I \rightarrow -S_I \tag{12}$$

Therefore these symmetric and antisymmetric combinations, corresponding to axion and photon are not going to be mantained in the presence on B in the analog QED language, since the "analog external electric potential" breaks the symmetry between particle and antiparticle and therefore will not mantain in time the symmetric or antisymmetric combinations. In fact if the analog external electric potential is taken to be a repulsive potential for particles, it will be an attractive potential for antiparticles, so the symmetry breaking is maximal.

IV. CONCLUSIONS

Pure axion and pure photon initial states correspond to symmetric and antisymmetric linear combinations of particle and antiparticle in the picture presented here. The reason these linear combinations are not going to be mantained in the presence on a non trivial B in

the analog QED language, is that the analog external electric potential breaks the symmetry between particle and antiparticle and therefore will not mantain in time the symmetric or antisymmetric combinations.

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